INVESTIGATION OF AIR TRANSPORTATION TECHNOLOGY AT PRINCETON UNIVERSITY, 1984

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SUMMARY OF RESEARCH

The Air Transportation Technology Program at Princeton University, a program emphasizing graduate and undergraduate student research, proceeded along four avenues during 1984:

- Guidance and Control Strategies for Penetration of Microbursts and Wind Shear
- Application of Artificial Intelligence in Flight Control Systems
- Effects of Control Saturation on Closed-Loop Stability and Response of Open-Loop-Unstable Aircraft

Areas of investigation relate to guidance and control of commercial transports as well as general aviation aircraft. Interaction between the flight crew and automatic systems is a subject of principal concern.

Recently, it has become apparent that severe downdrafts and resulting high velocity outflows present a significant hazard to aircraft on takeoff and final approach. This condition is called a microburst, and while it often is associated with thunderstorm activity, it also can occur in the vicinity of dissipating convective clouds that produce no rainfall at ground level. Microburst encounter is a rare but extremely dangerous phenomenon that accounts for one or two air carrier accidents and numerous general aviation accidents each year (on average). Conditions are such that an aircraft's performance envelope may be inadequate for safe penetration unless optimal control strategies are known and applied. While a number of simulation studies have been directed at the problem, there are varied opinions in the flying community regarding the best piloting procedures, and optimal control strategies remain to be defined.

Graduate student Mark Psiaki has undertaken a study of guidance and control strategies for penetration of microbursts when encounter is unavoidable. In work completed in 1984 [1], it was shown that simple control laws could greatly reduce an aircraft's response to wind shear. Although the response mechanism is the same, jet transport and general aviation aircraft behave somewhat differently in microbursts; the larger, heavier aircraft are more adversely affected by variations in the horizontal wind, while the smaller, lighter aircraft have greater difficulty with the downdraft.

The work in 1984 focused on the determination of optimal control strategies for the microburst encounter. The study began with the computation of optimal control histories using steepest-descent and second-order gradient algorithms. Once an envelope of safe flight has been determined for a typical jet transport, attention will be directed at a general aviation type, and optimal closed-loop control laws will be investigated. During 1984, a survey paper on the subject was presented at the NASA Workshop on Wind Shear/Turbulence Inputs to Flight Simulation and Systems Certification[2].

Undetected system failures and/or inadequately defined recovery procedures have contributed to numerous air carrier incidents and accidents. The infamous DC-10 accident at Chicago's O'Hare Airport, in which loss of an engine pod, subsequent loss of subsystems, and asymmetric wing stall led to disaster, provides a prototype for the kind of tragedy that could be averted by intelligent flight control systems. (An intelligent control system is one that uses artificial intelligence concepts, e.g., an expert systems program, to improve performance and fault tolerance.) Although many methods of modern control theory are applicable, the scope of the problem is such that none of the existing theories provides a complete and practical solution to the problem. At the same time, heuristic logic may be applicable, but it has yet to be stated in satisfactory format.

Graduate student David Handelman has begun to develop a knowledge-based reconfigurable flight control system that will be implemented with the Pascal programming language using parallel microprocessors. This expert system could be considered a prototype for a fault-tolerant control system that could be constructed using existing hardware. In a parallel effort, graduate student Chien Huang used the LISP programming language to investigate the utility of a string-oriented, recursive logical system in the same role. A principal distinction between this and the previous approach is that flight control code will be modified in response to control system failures.

One of the virtues of highly reliable electronic flight control systems is that an aircraft's stability and response, i.e., its closed-loop flying qualities, can be tailored to the pilot's needs. For reasons of performance and maneuverability, it may be desirable to design the aircraft so that its natural (unaugmented) modes of motion are unstable, with the understanding that the flight control system will provide the necessary stability by deflecting control surfaces to counter potentially divergent motions. Because control surfaces have limitations on their displacements and rates of travel, stability can be restored only within a bounded region about the trim point. If the aircraft's motions exceed the boundaries, the available control forces and moments will not be sufficient to prevent divergence.

Graduate student Prakash Shrivastava has been developing methodologies for determining the stability boundaries and control response for systems containing control saturation[3,4]. Analysis has been carried out using phase-plane plots, in which saturation and stability boundaries are represented by straight lines, stable trajectories approach equlibrium points, and unstable trajectories diverge to infinity. The analysis pertains to systems containing unequal saturation boundaries, as well as those with multiple saturating controls.

Future control-system engineers will benefit from design procedures that are computer-intensive, and it is important to create computer programs that allow designers to describe and analyze complex systems interactively. Russell Nelson has been developing a control-system design program based on the LISP language mentioned above *. Design algorithms will be based on classical concepts of transfer-function analysis, and LISP will allow multiloop systems to be assembled and tested within the computer.

The NASA grant supporting student research in air transportation technology has inestimable value in helping educate a new generation of engineers for the aerospace industry, and it is producing research results that are relevant to the continued excellence of aeronautical development in this country.

* Nelson, R. F., "Computer Aided Control System Design - Progress Report", Princeton University Independent Work Report, Jan. 1985. The goal of this independent project is to create a program, using LISP, that will serve as a tool in the design of control systems. The program will be menu driven and graphic with menu prompting. The frequency response of control systems will be examined through Bode analysis techniques. The program will enable the user to make rapid, interactive changes to a control system and then reevaluate the system's performance in order to optimize the design. The project also will give indication of LISP's usefulness in the field of control system design.

REFERENCES AND ANNOTATED BIBLIOGRAPHY

1. Psiaki, M. L., and Stengel, R. F., "Analysis of Aircraft Control Strategies for Microburst Encounter", AIAA Paper No. 84-238, Aerospace Sciences Meeting, Reno, Jan. 1984.

   Penetration of a microburst during takeoff or approach is an extreme hazard to aviation, but analysis has indicated that risks could be reduced by improved control strategies. Attenuation of flight path response to microburst inputs by elevator and throttle control was studied for a jet transport and a general aviation aircraft using longitudinal equations of motion, root locus analysis, Bode plots of altitude response to wind inputs, and nonlinear numerical simulation. Energy management relative to the air mass, a pitch-up response to decreasing airspeed, increased phugoid-mode damping, and decreased phugoid natural frequency were shown to improve microburst penetration characteristics. Aircraft stall and throttle saturation were found to be limiting factors in an aircraft's ability to maintain flight path during a microburst encounter.

2. Stengel, R. F., "Unresolved Issues in Wind-Shear Encounter", presented at the NASA Workshop on Wind Shear/Turbulence Inputs to flight Simulation and Systems Certification, Hampton, May, 1984.

   Much remains to be learned about the hazards of low-altitude wind shear to aviation. New research should be conducted on the nature of the atmospheric environment, on aircraft performance, and on guidance-and-control aids. In conducting this research, it is important to distinguish between near-term and far-term objectives, between basic and applied research, and between uses of results for aircraft design or for real-time implementation. Advances in on-board electronics can be applied to assuring that aircraft of all classes have near-optimal protection against wind shear hazards.

3. Shrivastava, P. C., and Stengel, R. F., "Stability Boundaries for Systems with Control Constraints", Proceedings of the 18th Conference on Information Science and Systems, Princeton, Mar. 1984.

   Although unstable systems can be stabilized using feedback control, constraints on the rates and magnitudes of control variables limit the region of stability. Stability boundaries must be evaluated during control system design to assure satisfactory system performance. This analysis becomes more relevant where compromises between the degree of plant instability and upper limits on the rates and magnitudes of control variables have to be made. This paper presents stability boundaries for linear feedback control laws. The method of normal-mode decomposition using the phase-plane approach appears to be well-suited to the evaluation. It is concluded that although the saturation boundaries are dependent on feedback gain magnitudes, the stability boundaries principally depend on the open-loop system dynamics and the allowable control deflection.

4. Shrivastava, P. C., and Stengel, R. F., "Stability Boundaries for Closed-Loop Systems with Control Constraints", Proceedings of the 23rd Conference on Decision & Control, Las Vegas, Dec. 1984, pp. 1326-1329.

   Constraints on the magnitudes of control variable limit the region where unstable systems can be stabilized using feedback control. Stability boundaries must be evaluated to assure satisfactory system performance. A method is presented to determine the stability boundaries for linear second-order plants with

saturating control and several classes of open-loop instability. In the saddle-point case, the modal axis of the stable mode centered on the equilibrium points and the saturation boundaries establish the regions of stability. For unstable nodes and foci, the stability boundaries are represented by unstable limit cycles enclosing the stable origin. The stability regions vary with changes in feedback gain. These results have fundamental significance for determining the degree to which unstable plants can be controlled in practical application.